Analysis of a Hypergolic Propellant Explosion
During Processing of a Launch Vehicles in the VAB

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ABSTRACT

NASA is developing launch vehicles to support missions to Low Earth Orbit (LEO), the moon and deep space. Whether manned or unmanned, the vehicle components will likely be integrated in the Vehicle Assembly Building (VAB) at Kennedy Space Center (KSC) and typically include a fueled spacecraft (SC) that sits on top of one or more stages. The processing of a fueled SC involves hazardous operations when it is brought into the VAB Transfer Aisle and lifted a significant height for mating with lower stages. Accidents resulting from these hazardous operations could impact unrelated personnel working in buildings adjacent to the VAB.

Safe separation distances based on the DOD Explosives Standards Quantity-Distance (Q-D) approach result in large IBD arcs. This paper presents site-specific air blast and fragmentation hazard analyses for comparison with the Q-D arcs as well as consequence and risk analyses to provide added information for the decision maker. A new physics-based fragmentation model is presented that includes: a) the development of a primary fragment list (which defines the fragment characteristics) associated with a hypergolic propellant explosion, b) a description of a 3D fragment bounce model, c) the results of probabilistic Monte-Carlo simulations (that include uncertainties in the fragment characteristics) to determine: i) the hazardous fragment density distance, ii) the expected number of wall/roof impacts and penetrations to over 40 buildings adjacent to the VAB, and iii) the risk to building occupants.

PROBLEM DESCRIPTION

NASA future plans may involve integration of launch vehicle components inside the high bays of the Vehicle Assembly Building (VAB) at Kennedy Space Center (KSC). An integration process typically involves several hazardous operations including the movement of a fueled spacecraft (SC) into the Transfer Aisle (TA) outside a high bay and then lifting the SC to a significant height for mating with the vehicle's lower stages. NASA is concerned with the hazards and risks to occupants of numerous buildings adjacent to the VAB (unrelated to the hazardous operations) if an explosion accident should occur in the TA or during mating operations. To assess the potential explosion effects, both air blast and fragmentation analyses were performed using an existing Orion and Service Module spacecraft design which is representative of a typical manned exploration SC.

During integration to the existing ARES-I launch vehicle design[1], a fueled Orion SC would be transported into the VAB transfer aisle, lifted up over 300 feet, and placed on top of a 2nd LOX/LH2 second stage which is mounted on a five segment 1st stage solid rocket motor stack (1st stage). The SC consists of a payload adapter, service module, crew capsule and launch abort system as shown in Figure 1.

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[1] The ARES I program was originally designed to replace the Space Shuttle's capability for taking astronauts to the International Space Station (ISS) as well as a re-supply capability but the program was recently cancelled.

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14. ABSTRACT
NASA is developing launch vehicles to support missions to Low Earth Orbit (LEO), the moon and deep space. Whether manned or unmanned, the vehicle components will likely be integrated in the Vehicle Assembly Building (VAB) at Kennedy Space Center (KSC) and typically include a fueled spacecraft (SC) that sits on top of one or more stages. The processing of a fueled SC involves hazardous operations when it is brought into the VAB Transfer Aisle and lifted a significant height for mating with lower stages. Accidents resulting from these hazardous operations could impact unrelated personnel working in buildings adjacent to the VAB. Safe separation distances based on the DOD Explosives Standards Quantity-Distance (Q-D) approach result in large IBD arcs. This paper presents site-specific air blast and fragmentation hazard analyses for comparison with the Q-D arcs as well as consequence and risk analyses to provide added information for the decision maker. A new physics-based fragmentation model is presented that includes: a) the development of a primary fragment list (which defines the fragment characteristics) associated with a hypergolic propellant explosion, b) a description of a 3D fragment bounce model, c) the results of probabilistic Monte-Carlo simulations (that include uncertainties in the fragment characteristics) to determine: i) the hazardous fragment density distance, ii) the expected number of wall/roof impacts and penetrations to over 40 buildings adjacent to the VAB, and iii) the risk to building occupants.

15. SUBJECT TERMS

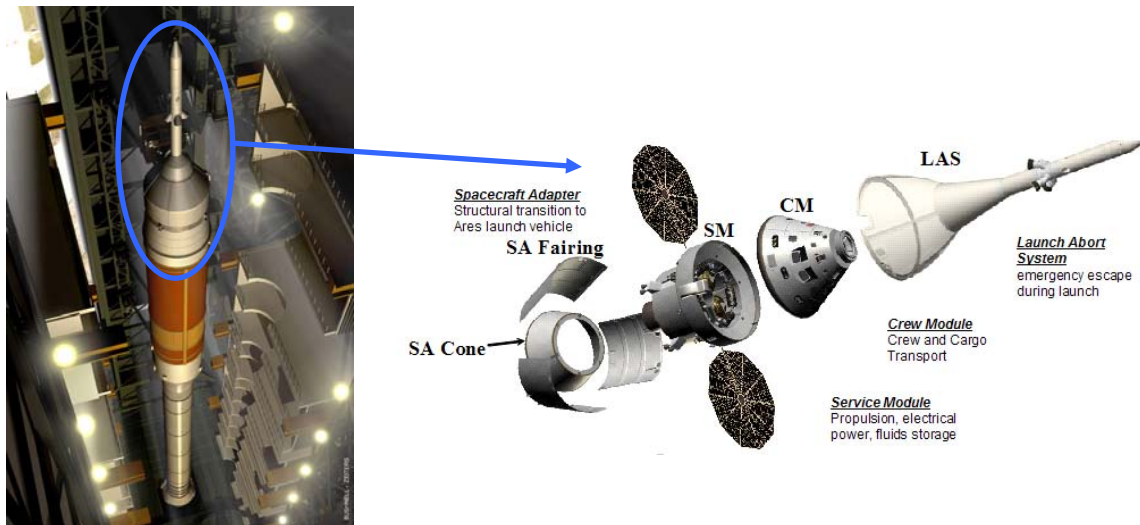| 16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
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Figure 1. Orion SC Positioned at Top of ARES-1 Vehicle.

The ARES-I first stage is a single, five-segment reusable solid rocket booster derived from the Space Shuttle Program's reusable solid rocket motor. The ARES I second stage is propelled by a J-2X main engine fueled by liquid oxygen and liquid hydrogen. The Orion Crew Exploration Vehicle (CEV) sandwiched between the Service Module (SM) and Launch Abort System (LAS) is similar in shape to the Apollo capsule, but significantly larger. The launch abort system atop the Orion capsule is capable of pulling the spacecraft and its crew to safety in the event of an emergency on the launch pad or at any time during ascent. Orion's power and propulsion systems are housed in the SM which is mounted directly below the capsule (see Figure 2). The propulsion system consists of a Delta II upper stage engine using nitrogen tetroxide and monomethyl hydrazine hypergolic propellants which are considered Hazard Division 1.1.
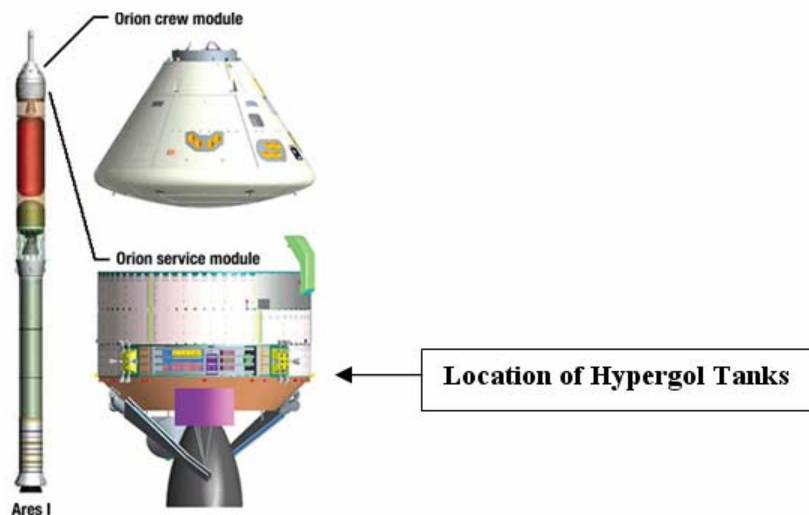

Figure 2. View of Spacecraft Propulsion System Located in Service Module.

The ARES-I (or other typical NASA launch vehicles) will likely be assembled in one of several VAB high bays. The locations of potential SC explosions were assumed to occur while the fueled SC is processed at ground level in the Transfer Aisle (TA) outside of a high bay or being mated to the lower stages at approximately 322 feet above ground level as shown in Figure 3.
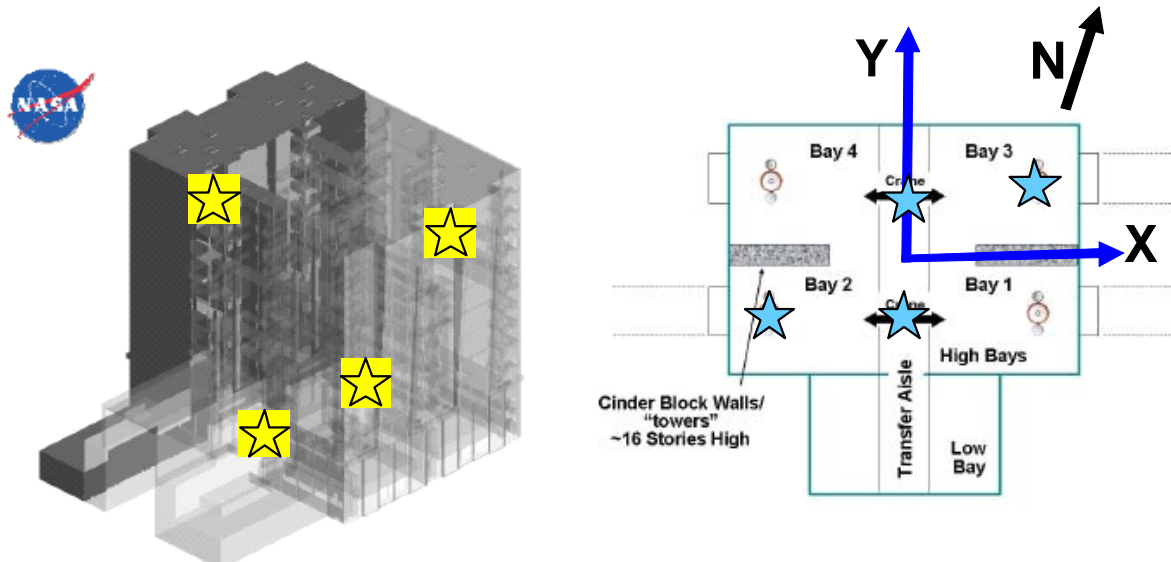
Figure 3. Location of Explosion Locations Considered.

EXPLOSION EVALUATION PROCESS

Figure 4 shows the four step process that the DOD Explosives Safety Board (DDESB) recommends for evaluating explosive hazards, consequences and risk in order to gain an explosives site plan approval. Note that all four steps do not have to be performed for approval; meeting the acceptance criteria for any of the four steps is sufficient. For example, if the explosives site plan is in conformance with the DOD Quantity-Distance (Q-D) criteria the other three steps need not be performed. Similarly if the risk is shown to be acceptable it can be used to gain approval even if Q-D safe separation distances are violated.
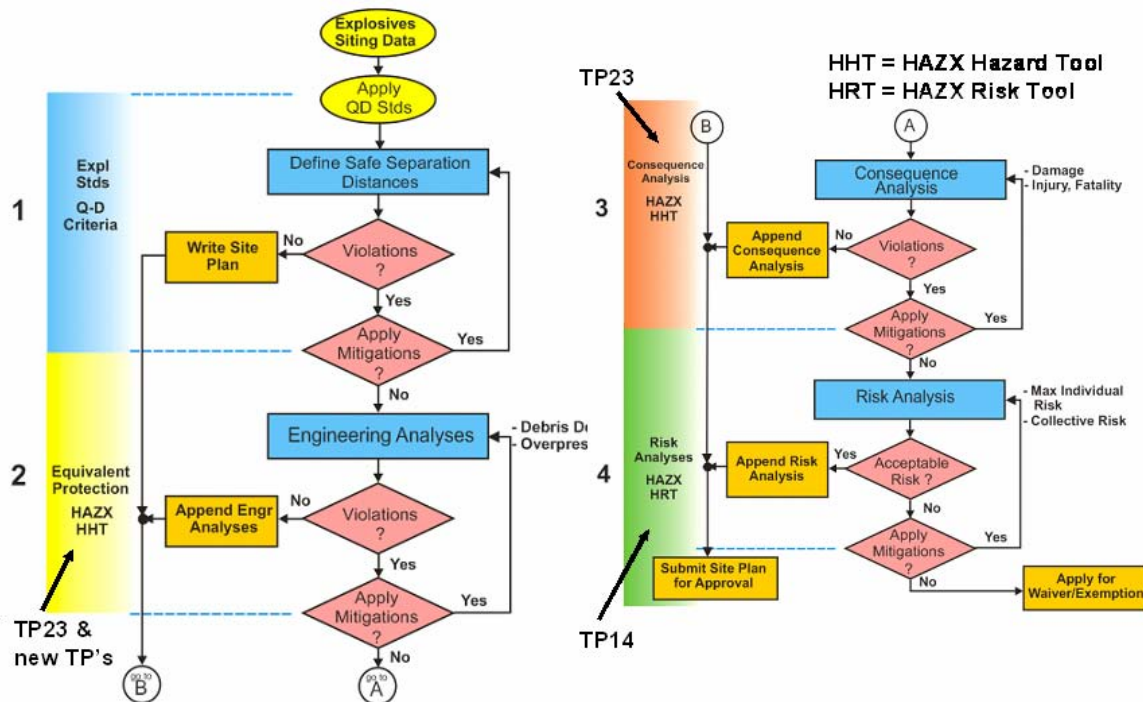

Figure 4. DDESB Process for Explosives Site Plan Approval.

It is insightful, however, to perform all four steps as each one provides the decision-maker with additional information that is helpful in understanding both hazards and risks when making explosives siting decisions (such as implementing potentially costly mitigations). The following sections present the analysis results for each step considering the four SC hypergolic propellant explosion scenarios that could occur in the VAB.

QUANTITY-DISTANCE ANALYSIS

The Quantity-Distance safe separation distances were determined using the "DOD Ammunition and Explosives Safety Standards", DOD 6055.9-STD, Reference [1] which is the parent explosives safety standard document used by the services. NASA-STD-8719.12, Safety Standard for Explosives, Propellants, and Pyrotechnics", Reference [2], is NASA's equivalent standard based on the parent document and gives the same separation distances for the accident events examined in this study. To determine the Q-D separation distances, the Net Explosion Weight (NEW) of the accident must be defined. Based on DOD 6055.9-STD, the yield factor for hypergolic propellant is 5% for static accidents and 10% for dynamic accidents.[2] NASA requested that the conservative yield factor of 10% be used for all VAB explosion accident simulations even though relevant test data indicates much lower yield factors. The total amount of hypergolic propellant stored in the Orion spacecraft is 18,545 lbs; therefore, the NEW is 0.10 x 18,545 = 1,855 lbs, TNT.

Based on the 1,855 lb NEW, the Inhabited Building Distances (IBD's), that are used to protect personnel unrelated to a hazardous operation, were determined for air blast and fragmentation. The IBD distance for air blast is the distance at which the incident overpressure from the explosion drops below 1.2 psi. For fragment throw, the IBD is based on limiting the hazardous fragment[3] density to less than one per 600 square feet. For a NEW of 1,855 lb, fragmentation hazards control and the IBD distance is 1250 feet (see Figure 5). As can be seen, the fragmentation IBD encroaches on numerous existing occupied buildings adjacent to the VAB.

EQUIVALENT PROTECTION ANALYSIS

If Q-D safe separation distances impact proposed operations, the DDESB explosives site plan process allows the requesting organization to perform site-specific equivalent protection analyses. Site-specific equivalent protection analyses are used to determine if the IBD distance(s) based on the DOD Explosives Standard are overly conservative. ACTA performed both air blast and fragmentation equivalent protection analyses; they indicated that fragment throw <u>does</u> control over air blast. The fragment equivalent protection analyses involved the development of an Orion spacecraft-specific primary fragment list and incorporating a secondary debris list (which defines debris thrown from the VAB internal structure and exterior walls) based on work done by Engineering Analysis Inc. (EAI), References [4] and [5].

AIR BLAST ANALYSIS

The equivalent air blast safe separation distance was based on determining the distance at which the incident overpressure drops below 1.2 psi (the IBD level). To determine the overpressure and impulse as a function of distance, a Transfer Aisle explosion (the controlling case) was modeled as a detonation resulting from a ground level hemispherical charge (see Figure 6). Again, it was conservatively assumed that the VAB internal and external structure would not attenuate the blast wave. ERDC's CONWEP program [3] was used to predict the overpressure and impulse as a function of distance. The table shown in Figure 6 summarizes the incident and reflected overpressure and impulse. As Figure 6 and Figure 7 show, the IBD distance based on our analysis indicates a safe separation distance for air blast of 483 feet from the center of the explosion and is much less than the 1250 foot IBD fragmentation distance.

FRAGMENTATION ANALYSIS

The fragment equivalent protection analyses involved the development of a spacecraft-specific primary fragment list and incorporating a secondary debris list (which defines debris thrown from the VAB internal

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[2] A static accident is associated with controlled engine testing and a dynamic accident with launch operations.
[3] The DOD explosives standard considers a hazardous fragment as one having a KE of 58 ft-lbs or greater.

structure and exterior walls) based on work done by Engineering Analysis Inc. (EAI). The following subsections describe the development of the primary fragment and secondary debris lists.
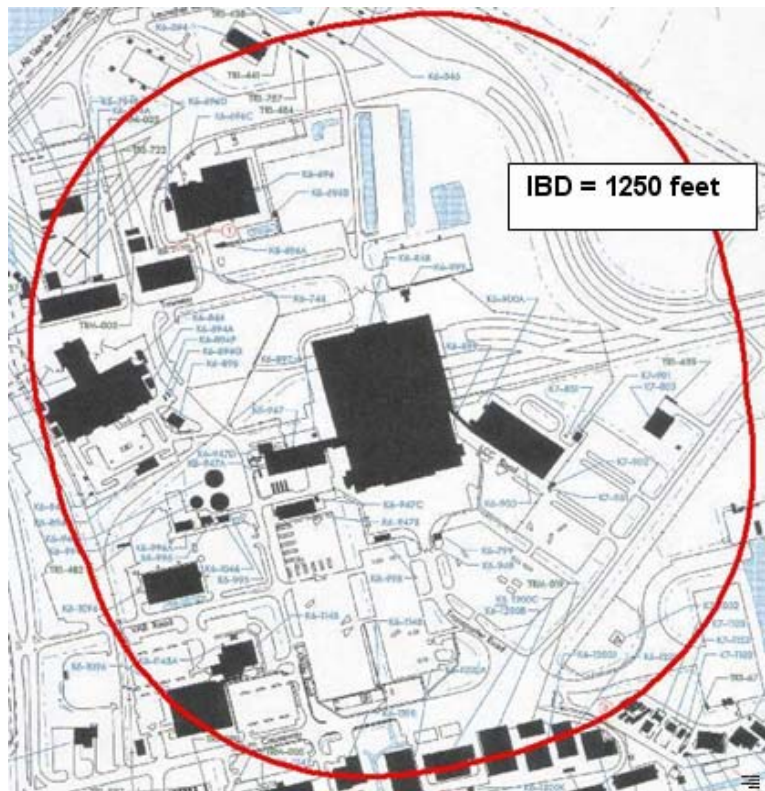

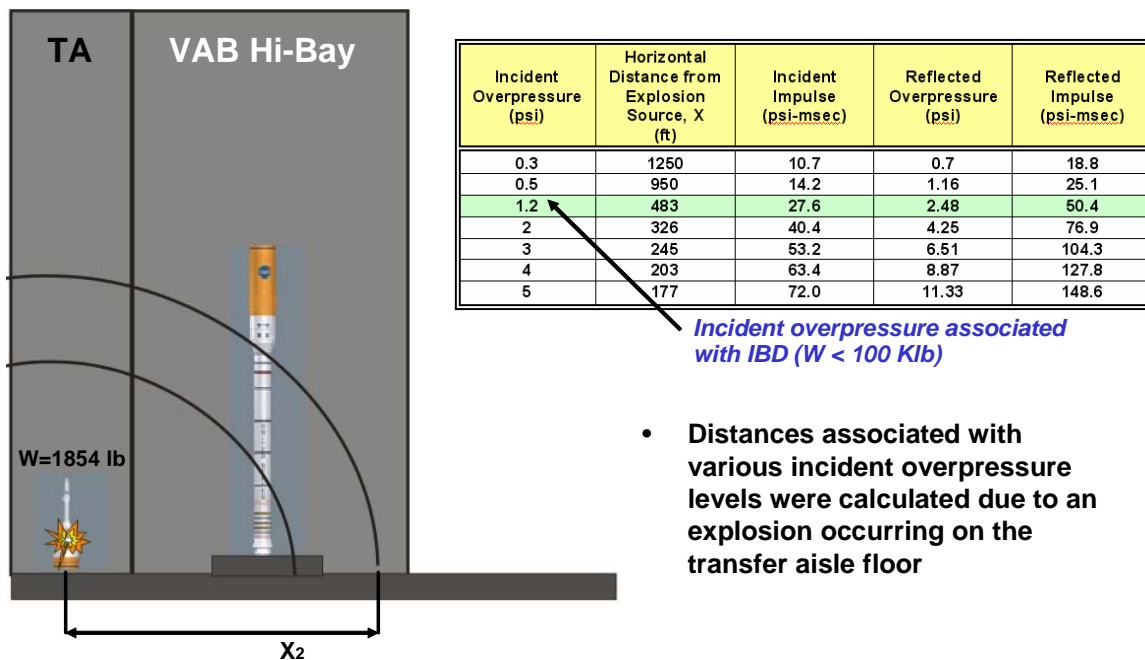**Figure 5. Q-D Explosives Standard Q-D Fragmentation Arc.**

Incident Overpressure (psi)	Horizontal Distance from Explosion Source, X (ft)	Incident Impulse (psi-msec)	Reflected Overpressure (psi)	Reflected Impulse (psi-msec)
0.3	1250	10.7	0.7	18.8
0.5	950	14.2	1.16	25.1
1.2	483	27.6	2.48	50.4
2	326	40.4	4.25	76.9
3	245	53.2	6.51	104.3
4	203	63.4	8.87	127.8
5	177	72.0	11.33	148.6

Incident overpressure associated with IBD (W < 100 Klb)

- **Distances associated with various incident overpressure levels were calculated due to an explosion occurring on the transfer aisle floor**

Figure 6. Overpressure and Impulse as a Function of Distance (explosion at 322 feet).

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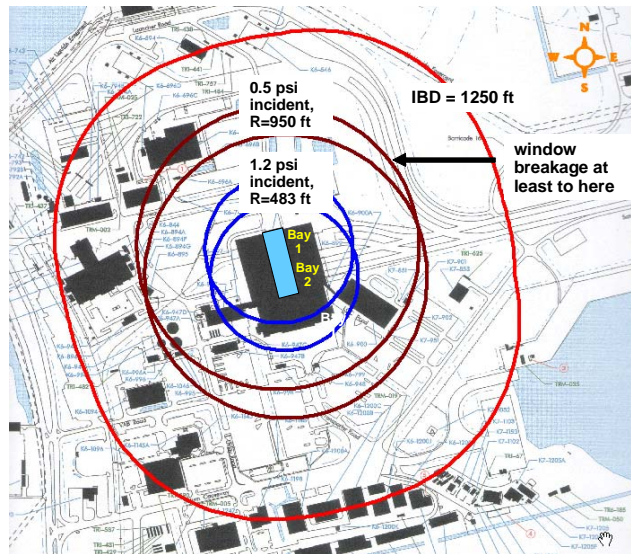
Figure 7. Transfer Aisle Explosions – IBD (1.2 psi) and 0.5 psi Contours.

Primary Fragment List

The primary fragment list was developed to represent primary fragmentation thrown as the result of a hypergolic propellant detonation inside the service module of the Orion spacecraft. Spacecraft hardware components, locations, weights and shapes were determined based on dimensional drawings, detailed material lists and photographs (see Figure 8). Based on these data, over 20,000 fragments were included in the fragment breakup list. The list includes intact components such avionics packages, batteries and other bolted down packages as well as distributed fragments representing the breakup of the spacecraft exterior shell, panels and cabling. A modified Gurney method was used to estimate fragment initial velocities. Reference [4] provides details of the primary fragment list development procedures.
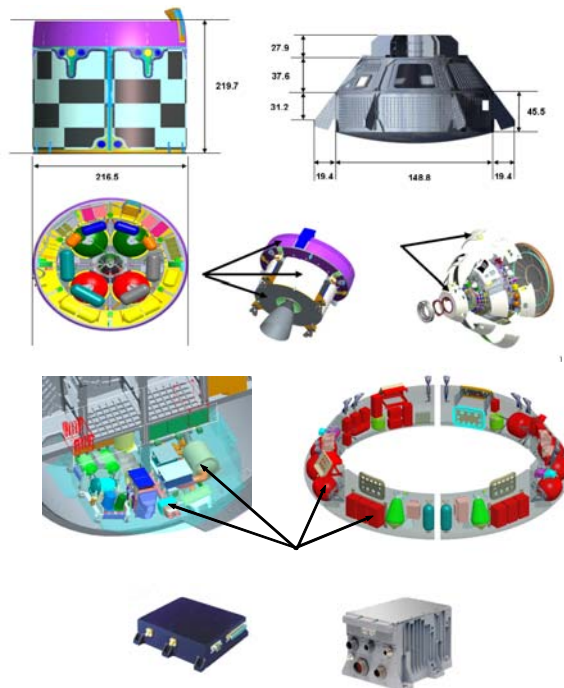
Figure 8. Samples of Spacecraft Hardware.

Secondary Debris List

The secondary debris list representing the debris thrown as a result of the breakup of work platforms and interior/exterior VAB walls and structure was developed by Engineering Analysis Inc. (EAI). EAI determined the air blast loading along discrete ray paths as shown in Figure 9 and determined the potential failure of both internal structures and external wall cladding. Structural failures and residual air blast loading were used to determine the secondary debris list and the associated initial velocities. Reference [5] provides details on the EAI secondary debris list development procedure.

HAZARDOUS FRAGMENT DENSITY DISTANCE

The fragmentation analyses were carried out using DebrisHAZ, a program developed at ACTA to perform detailed, site- and vehicle-specific explosion fragment hazard simulations. The combined primary fragment and secondary debris list included hundreds of fragment groups (and thousands of individual fragments) with different nominal weights, ballistic coefficients, velocities, takeoff angles, etc. Thousands of random drag-corrected trajectory simulations were run including the consideration of bounce and roll to account for uncertainty in the fragment parameters. A new 3D physics-based bounce/roll model was used to predict each fragment's path after first impact based on its shape and ground contact characteristics (see Figure 10); details of the bounce model are presented in a companion paper [6].

The results of the random fragment/debris throw simulations were averaged to determine the hazardous fragment density distance (HFDD) based on the pseudo-trajectory normal method of recording hazardous fragment effects. Figure 11 shows the envelope of the HFDD's from all four explosion scenarios. The maximum HFDD distance is approximately 900 feet (controlled by EAI's secondary debris list in the northeast and southwest directions). The HFDD based on primary fragments is limited to approximately 500 feet (see Figure 12). The HFFD's of 500 or 900 feet based on the equivalent protection analysis are much less than the 1250 foot fragment HFFD specified by the Explosives Standards.
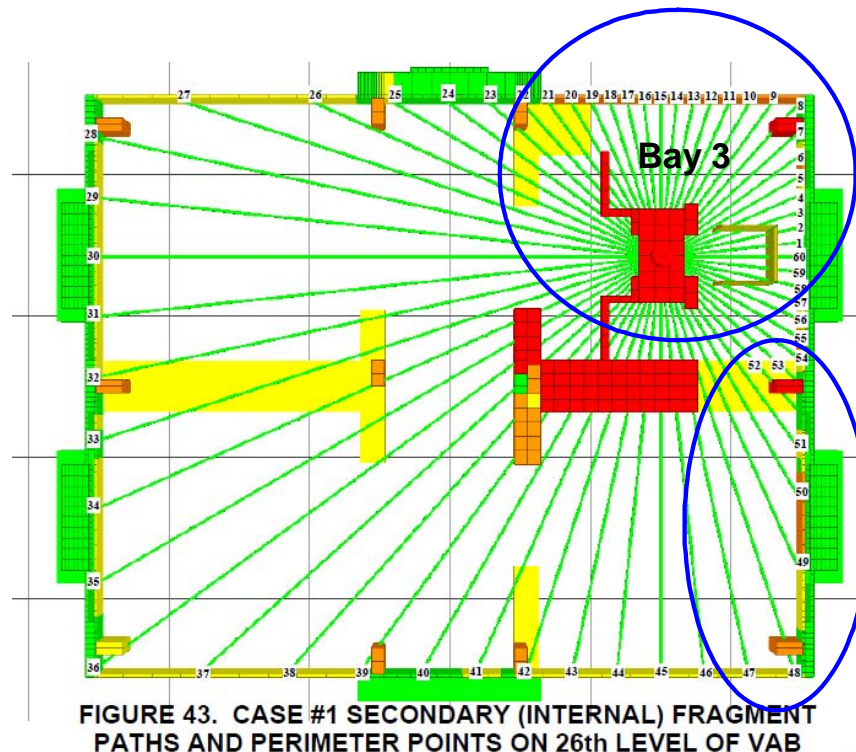

FIGURE 43. CASE #1 SECONDARY (INTERNAL) FRAGMENT PATHS AND PERIMETER POINTS ON 26th LEVEL OF VAB

Figure 9. EAI's Secondary Debris Path Schematic – High Bay 3 at 322 feet.
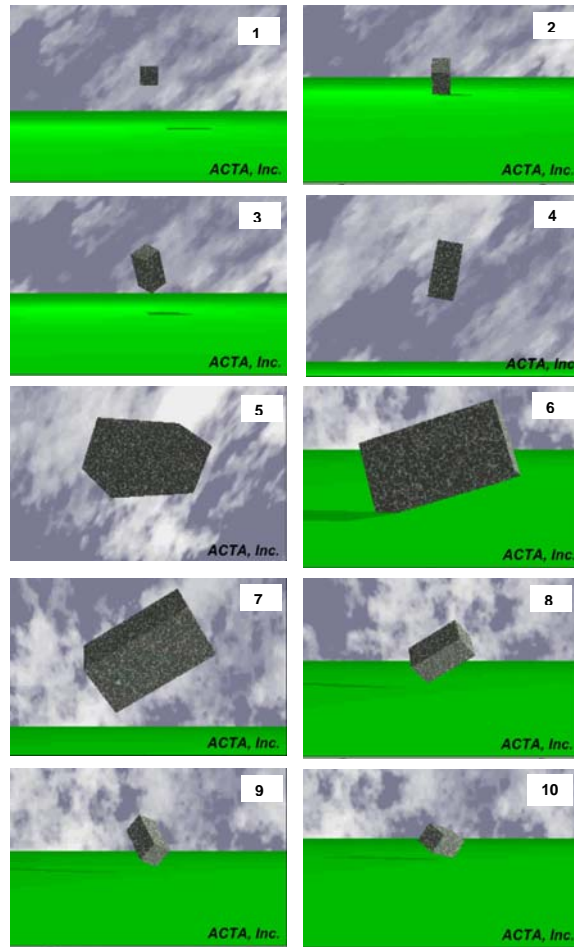
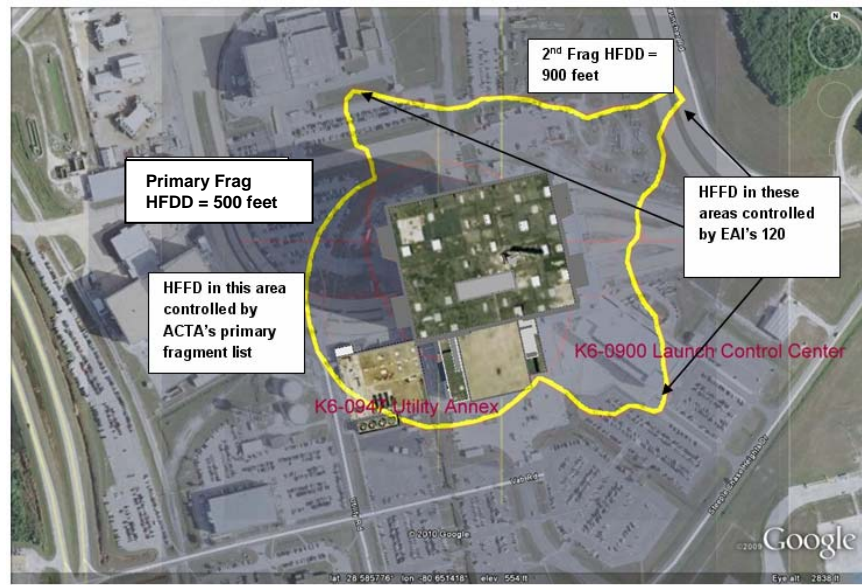**Figure 10. Sample of 3D Physics-Based Fragment Bounce Model.**

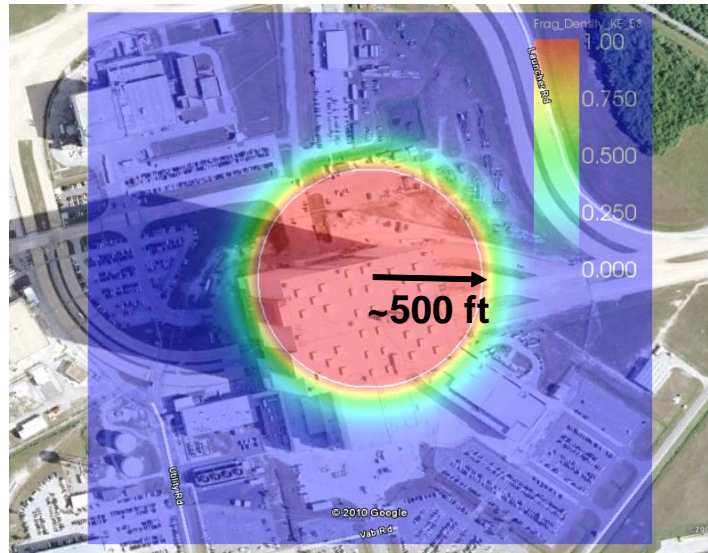**Figure 11. Envelop of Fragmentation Hazardous Fragment Density Distance (All Four Scenarios).**

Figure 12. HFDD Based Only on Primary Fragment Throw from High Bay 3 at 322 feet.

CONSEQUENCE ANALYSIS

The Q-D and equivalent protection analyses are used to determine the "hazards" (air blast overpressure and hazardous fragment density); they do not consider the associated consequences in terms of damage to structures, window breakage and injury to people <u>given</u> an explosion occurs. It is well known that the air blast IBD (1.2 psi incident overpressure) will prevent significant damage to conventionally built structures beyond IBD; however, window breakage can occur at distances well beyond IBD and structural damage and window breakage could occur inside IBD and potentially hazard existing building occupants.

Air blast and fragment throw consequence analyses were performed using ACTA's HAZX and DebrisHAZ explosion assessment software. To perform these analyses, the locations and attributes of buildings adjacent to the VAB within a 7,000 foot radius were entered. The necessary building data were obtained from the Air Force 45SW/SELR and included wall/roof construction types, window types/sizes/numbers and maximum population counts.

These data were input into HAZX and a hypergolic propellant explosion of 1855 lb, TNT was simulated to determine the injury to people in the open, structural damage, window breakage and injury to building occupants due to air blast. Figure 13 shows the areas adjacent to the VAB where people in the open could be injured due to air blast. At distances beyond about 400 feet (the nearest wall of the Launch Control Center, LCC) people in the open will suffer at most temporary loss of hearing and ear drum ringing.[4]

Structural damage due to air blast given a hypergolic propellant explosion occurs is shown in Figure 14. As expected, little damage will occur outside of IBD[5] for buildings of conventional construction and the only building inside of IBD that could be damaged is part of the VAB (the LCC has a blast resistant design). Figure 15 and Figure 16 show the expected window breakage and the expected number of casualties resulting from glass shards being thrown into buildings. Based on the window inventory received from the 45SW/SELR, there is a high likelihood that several existing buildings adjacent to the VAB will incur window breakage and glass shards thrown inward could cause serious injuries to occupants.

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[4] People can withstand greater blast overpressure levels than weaker buildings as the body is compliant and can absorb energy.

[5] IBD is established to prevent damage to structures that could hazard occupants. But, the Explosives Standards note that window breakage could be an issue and buildings with windows facing the explosion should be avoided.
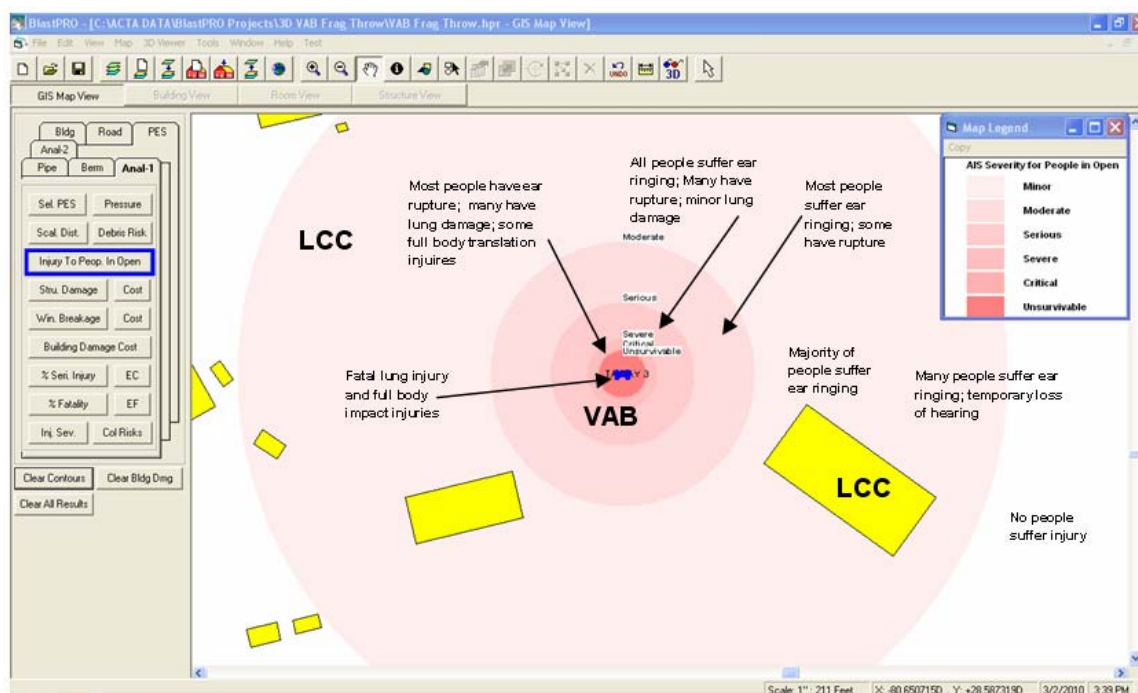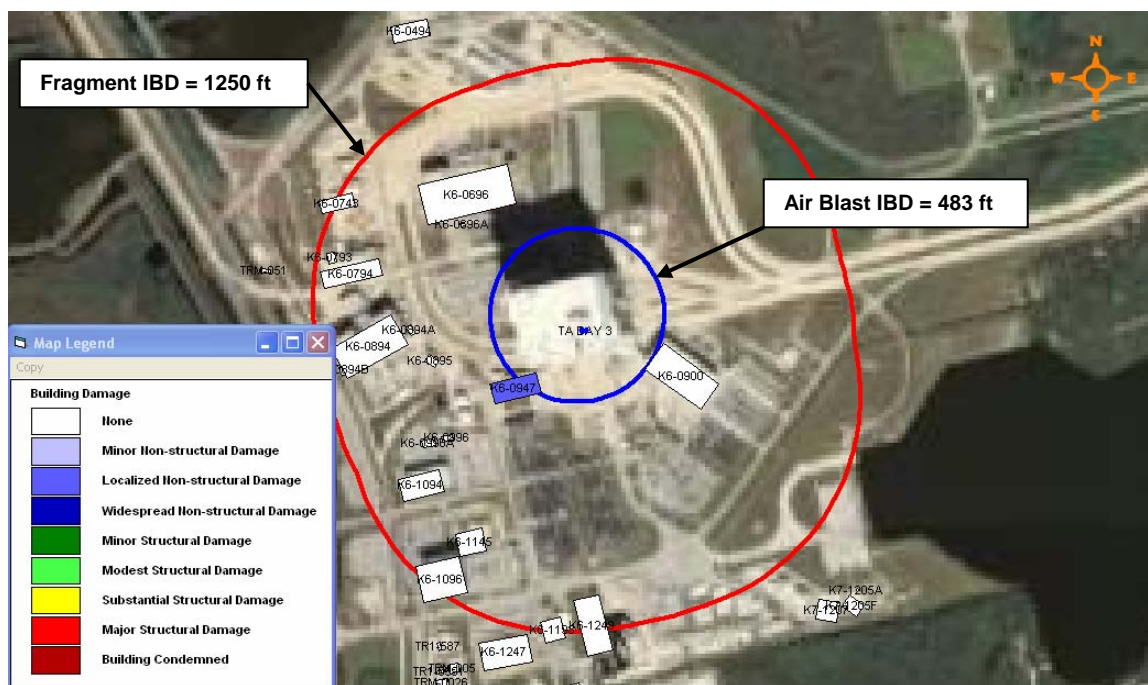
Figure 13. Injury to People in the Open.

Figure 14. Structural Damage due to Air Blast.

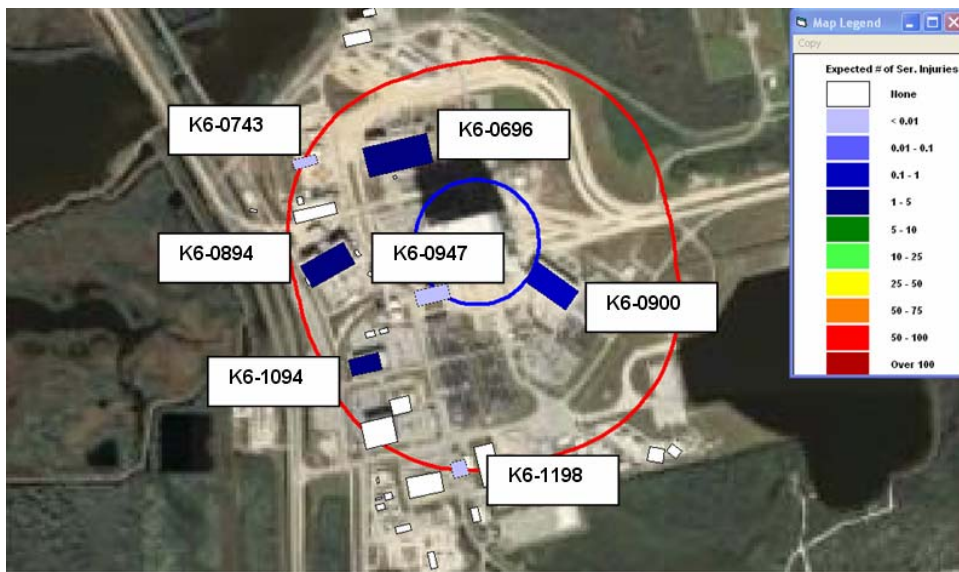**Figure 15. Window Breakage due to Air Blast.**

Figure 16. Expected Number of Serious Injuries or Greater due to Air Blast.

The consequences to occupied buildings adjacent to the VAB due to fragmentation were determined by recording the potential fragment impacts and penetrations of each building's walls and roof. To accomplish this, the footprints of the occupied buildings were extruded upward to their respective heights (as shown in Figure 17) and fragment penetration energies assigned to the walls and roof of each building based on their construction characteristics. Thousands of random simulations of primary and secondary fragment/debris throw (using the lists previously described) were performed and the number of wall/roof impacts and penetrations recorded for each simulation (Figure 18 shows one such simulation). The impacts and penetrations were averaged across all simulations to determine the expected number of impacts and penetrations.

The results of the fragment consequence analysis indicated people in the open and numerous buildings adjacent to the VAB could be impacted by fragments; however, only three buildings would likely suffer roof penetration due to their light construction and potentially hazard occupants.

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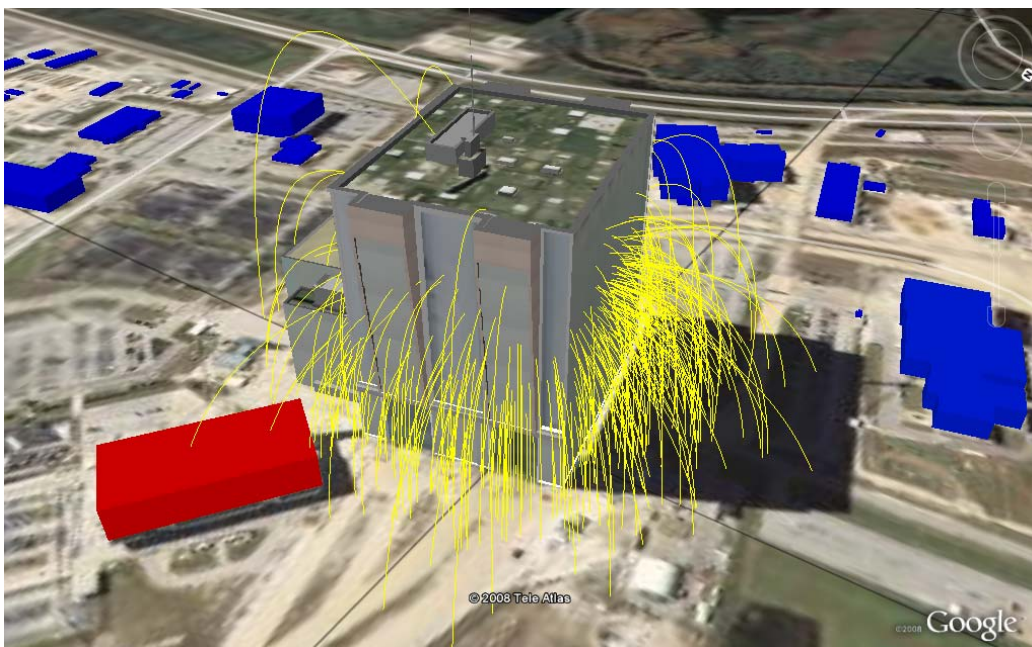**Figure 17. Buildings Included in the Fragment Consequence Analysis.**

Figure 18. One Random Simulation of Fragment Throw.

RISK ANALYSIS

The previous analyses did not take into account the probability that a spacecraft handling or processing accident could result in a hypergolic propellant explosion. As part of this study, ACTA estimated the probability of a spacecraft handling/processing accident and performed simplified quantitative risk analyses (QRA's) to determine if the risk to people working adjacent to the VAB (but unrelated to hazardous operations in the VAB) were acceptable.

The probability of a handling or processing accident involving the fueled spacecraft inside the VAB was conservatively estimated based on historical operations/accidents recorded at VAFB, CCAFS and KSC over the last several decades. The per mission accident probability was estimated to be 1.4×10^{-3}.

Since NASA has not adopted acceptable risk criteria for pre-launch operations, two current criteria were considered:

1. Range Commander Council's Flight Safety Guidance (RCC 327-01), Reference [7] – they recommend that the following three risk metrics be considered: a) maximum individual casualty and fatality risk per mission, b) group casualty and fatality risk per mission, and c) annual casualty and fatality group risk.

2. DDESB Conventional Weapons Criteria - they currently recommend that only the maximum individual and group fatality risk on an annual basis be considered.

The controlling acceptable risk metric for the explosion of a fueled spacecraft inside the VAB is the RCC's per mission metric for maximum individual and group casualty risk. Table 1 shows the computed casualty risks based on ACTA's QRA analyses compared to the RCC acceptable risk levels for unrelated personnel.

Table 1. Risk Acceptability (unrelated) based on RCC per Operation Casualty Requirements.

Risk Metric	Vulnerability	Computed Risk		RCC Acceptable Casualty Risk (unrelated)
		w/ windows & fragments	fragments only	
Maximum Individual	Casualty	110×10^{-6} (Bldg 0894)	0.17×10^{-6} (Bldg 0696)	1×10^{-6}
Group	Casualty	$28,000 \times 10^{-6}$	79×10^{-6}	100×10^{-6}

The casualty risk is dominated by window breakage for several buildings inside of IBD. When window effects are eliminated from these buildings (e.g., by adding blast film), fragment impact hazards dominate and the risk becomes acceptable.

Table 2 shows the computed <u>fatality</u> risks based on ACTA's QRA analyses compared to the DDESB's acceptance criteria for unrelated personnel. Because the DDESB does not consider casualties due to window breakage, the computed risks are acceptable and no mitigations are required to the existing buildings adjacent to the VAB.

Table 2. Risk Acceptability (unrelated) based on DDESB Fatality Requirements.

Risk Metric	Computed Fatality Risk (fragments only)	DDESB Acceptable Fatality Risk (per year)
Maximum Individual	4.7×10^{-8} (Bldg 0894)	1×10^{-6}
Group	4.8×10^{-6}	1×10^{-5}

CONCLUSIONS

This paper summarizes a study performed to evaluate the explosion hazards, consequences and risk to personnel in the open and located in existing buildings adjacent to the VAB due to the processing of a fueled spacecraft inside the VAB. Four explosion analyses were performed:

1. Quantity-Distance (Q-D) – based on the DOD Explosives Standard, the Inhabited Building Distance (IBD) to protect people unrelated to hazardous operations inside the VAB was determined to be 1250 feet (based on fragmentation).

2. Equivalent Protection – based on site-specific and accident-specific hazard analyses, the IBD fragmentation distance controls; it is approximately 500 feet for primary fragmentation (based on ACTA's fragment list) and 900 feet for secondary debris (based on EAI's debris list).

3. Consequences – based on site-specific and accident-specific damage and injury analyses, air blast resulting from a hypergolic propellant explosion in the VAB could break windows of several buildings <u>inside</u> of IBD and inward flying shards could injury occupants. Inside of IBD, fragments will also pose a hazard to people in the open and to occupants of several adjacent buildings (note that low-flying fragments that can penetrate windows were not considered). Outside of IBD, building occupants and people in the open adjacent to those building are very unlikely to be hazarded by thrown fragments.

4. Risks - simplified casualty and fatality risk analyses that included the probability of a hypergolic propellant explosion occurring inside the VAB produced different conclusions. If the RCC recommendations for risk acceptability are used (which include the consideration of casualties), the risks are unacceptable. If the DDESB recommendations for risk acceptability are used (which are based strictly on annual fatality), the risks are acceptable.

The four-pronged explosion analysis approach provides valuable insights into the potential problems that could occur during handling and processing of a fueled spacecraft inside the VAB. Windows on several buildings adjacent to the VAB are likely to be broken due to air blast; therefore mitigations to prevent injuries to building occupants by installing blast film and/or by moving people in the building perimeter away from windows facing the VAB are being considered. Several buildings are also susceptible to fragment impact and penetration inside IBD and NASA is considering mitigations to minimize the risk.

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[7]   RCC Standard 21-07, "Common Risk Criteria for National Test Ranges", prepared by Range Safety Group Risk Committee, June 2007.

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Outline

- **Problem Description**
- **Explosives Safety Analysis Process**
- **Q-D Siting**
- **Equivalent Protection Analysis**
- **Consequence Analysis**
- **Risk Analyses**
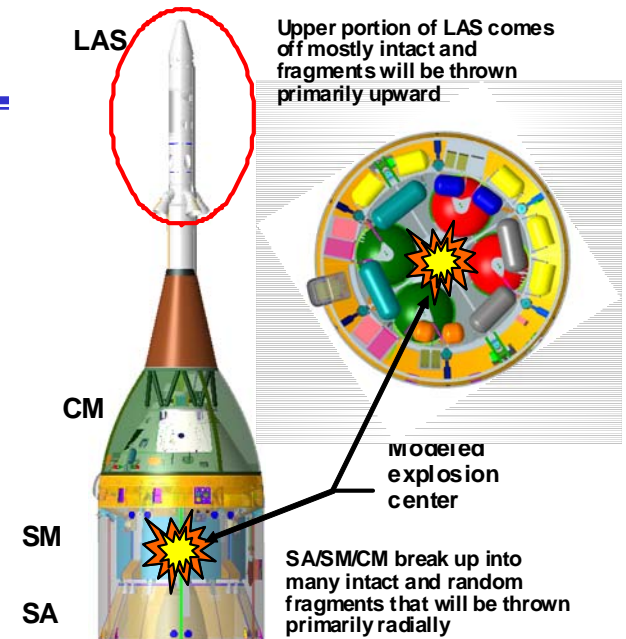- **Recommendations & Conclusions**

Spacecraft (SC) Processing in VAB

- **NASA plans to integrate spacecraft with a heavy lift vehicle inside the vehicle assembly building at KSC**

- **The spacecraft evaluated is fueled by liquid propellant (HD 1.1) representing an explosives hazard**
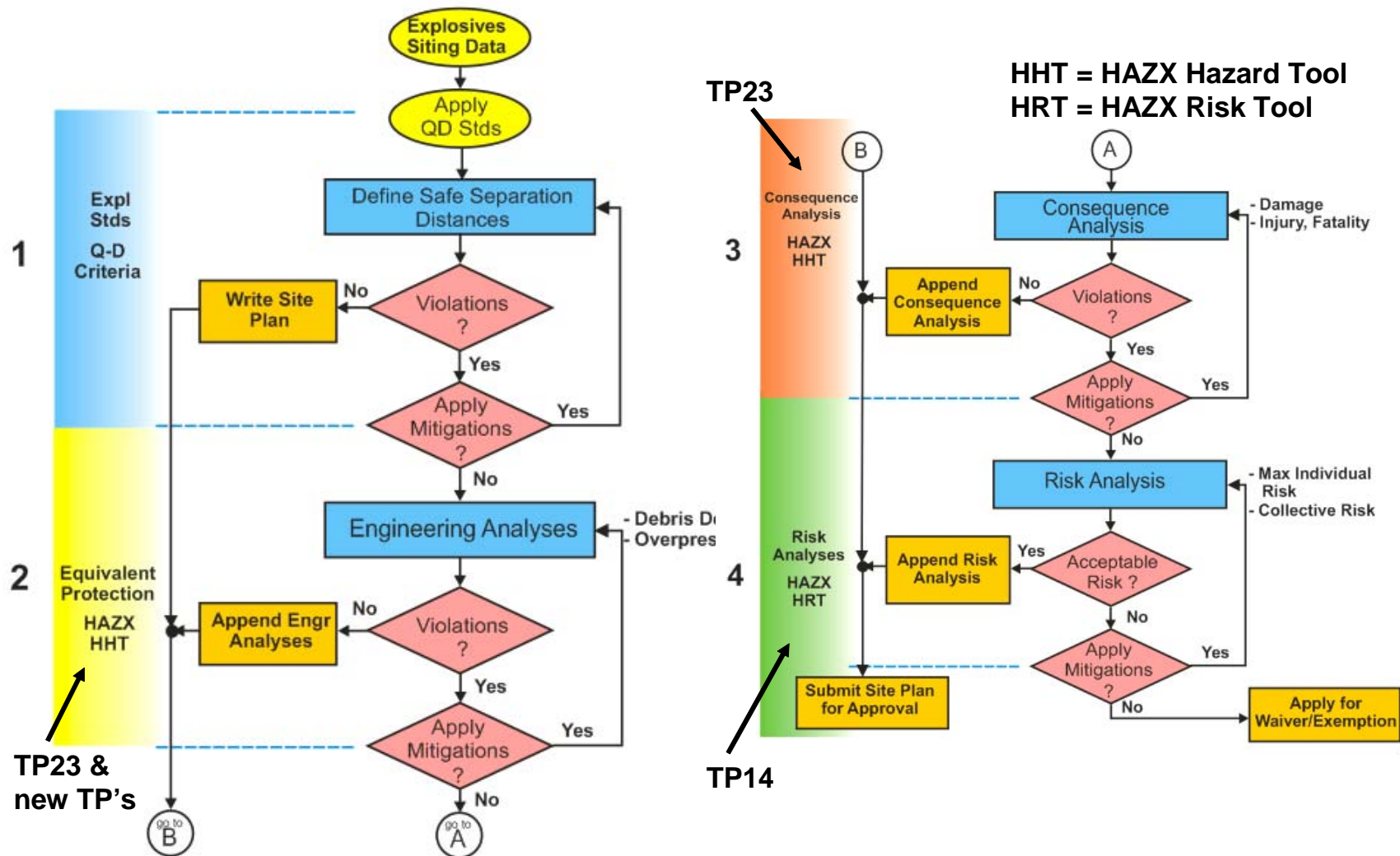
    - *The ARES SC was used for the analyses*

3
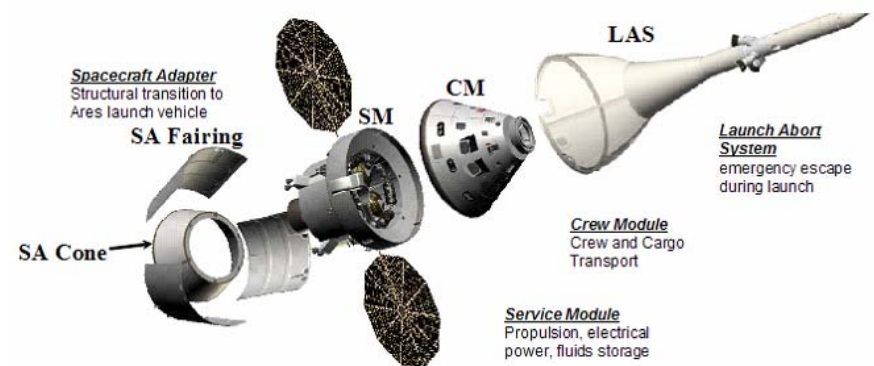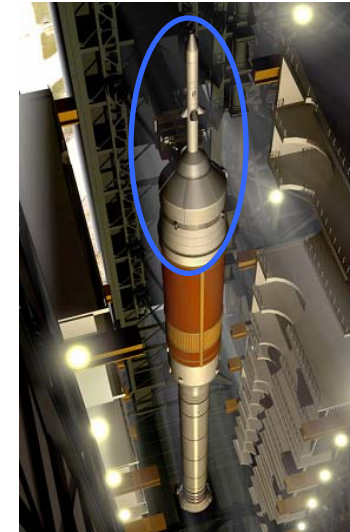
Problem Description

- **The hypergol tanks are located in the SC service module**
- **Explosion scenarios were defined for handling operations in the VAB transfer aisle and during mating operations to the vehicle in the Hi-Bays at 322 ft above ground**

LAS

Upper portion of LAS comes off mostly intact and fragments will be thrown primarily upward

CM

SM

SA

Modeled explosion center

SA/SM/CM break up into many intact and random fragments that will be thrown primarily radially

Y   N   X

Bay 4   Bay 3

Crane

Bay 2   Bay 1

High Bays

Cinder Block Walls/ "towers" ~16 Stories High

Transfer Aisle

Low Bay

4

Explosives Safety Analysis Process

Quantity-Distance Siting Analysis

- **Total Amount of hypergol propellant = 18,545 lbs**

- **Explosives Standard Yield Factor = 10%**

- **NEWQD = 1,855 lbs, TNT, HD 1.1**

- **IBD = 1250 feet (controlled by fragmentation)**
  - *IBD(blast) = 491 ft*

- **There are numerous occupied buildings inside IBD**

Occupied Buildings

IBD = 1250 feet

VAB

Equivalent Protection Analysis
(for fragmentation)

2 Equivalent Protection HAZX HHT

- IBD = distance at which the number of hazardous fragments (KE ≥ *58 ft-lbs)* drops below 1/600 ft^2

- A spacecraft-specific primary fragment list was developed for a 1,855 lb TNT explosion in its service module

    - *Fragment characteristics include, weight, shape, area, material, ballistic coefficient, takeoff location, velocity and angle*

    - *The primary fragment list conservatively contained over 20,000 fragments*

- A secondary debris list was appended that defined the internal VAB platforms and exterior wall debris resulting from the air blast damage
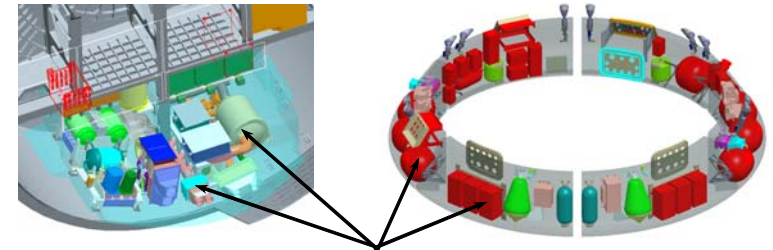

Intact components
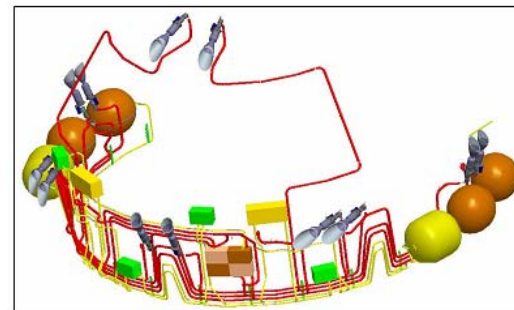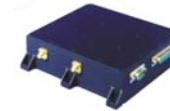
piping components

ACTA Inc

7

NASA

# Hazardous Fragment Density Distance (primary fragmentation only)

- **The primary fragment list was used to perform thousands of random simulations of a spacecraft explosion at 322 feet above the ground using the the DebrisHaz software & the HAZX Hazard Tool (HHT)**

  - *The VAB internal/external structure was conservatively assumed to not block primary fragments*

  - *3D fragment bounce/roll was included in PTN analysis*

- **The vehicle-specific HFDD was ~500 ft versus the 1250 ft Q-D safe distance**
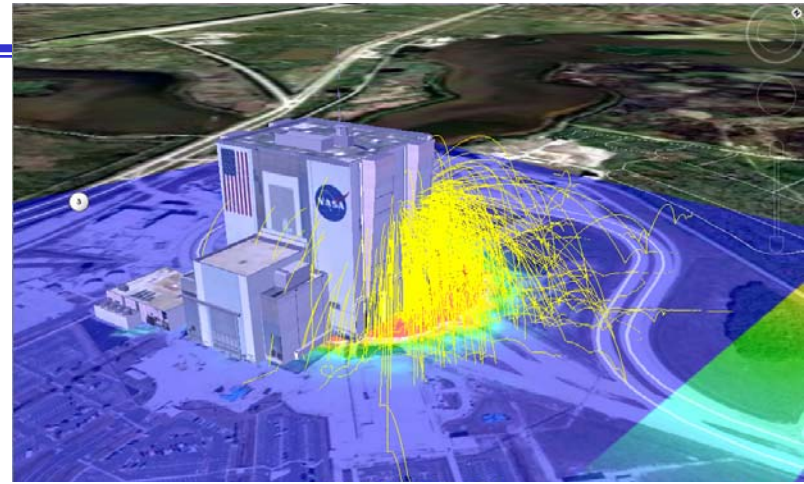

Trajectories from one random accident simulation

~500 ft
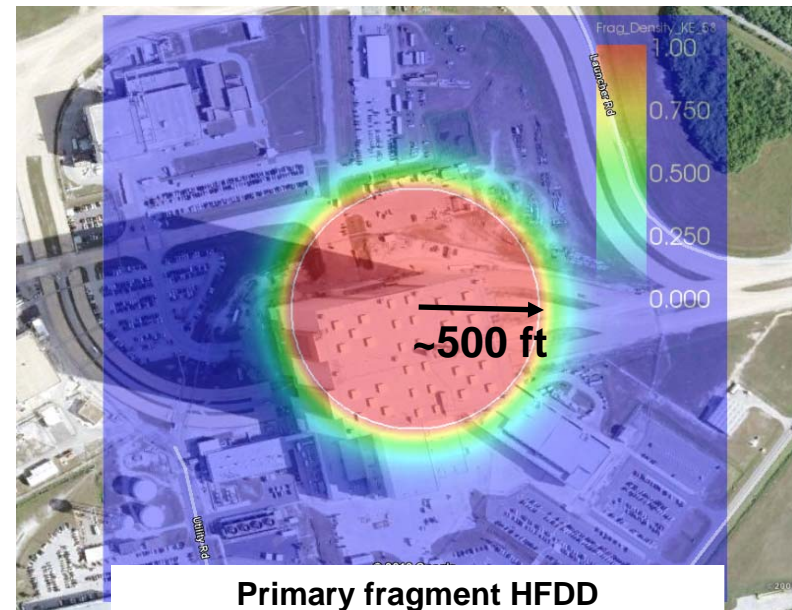
Primary fragment HFDD

8
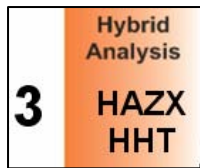
Air Blast Consequence Analysis
(given explosion occurs)

(note: NASA does not currently accept consequence analyses for ground safety)

- **Serious injury as well as fatality were considered**

- **Serious injury/fatality to people in open is limited to 350 ft**

- **Significant structural damage does not occur outside IBD**

- **Window breakage, however, can occur for several buildings adjacent to the VAB well within IBD & outside IBD**
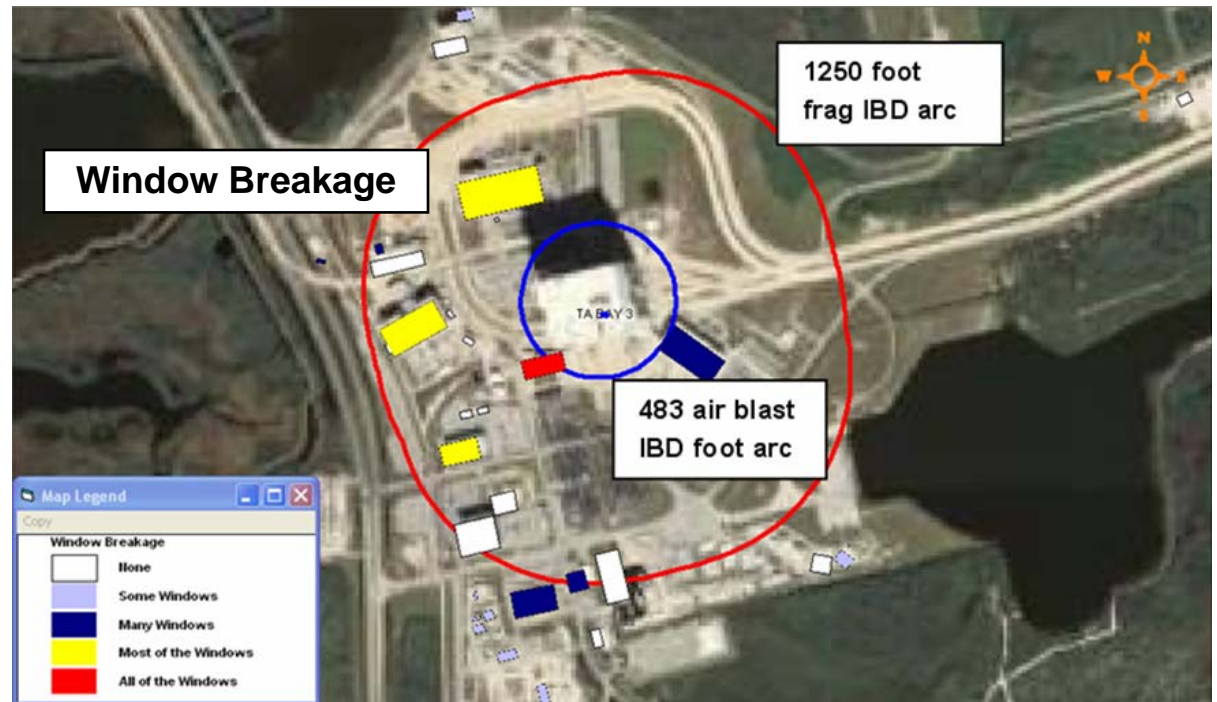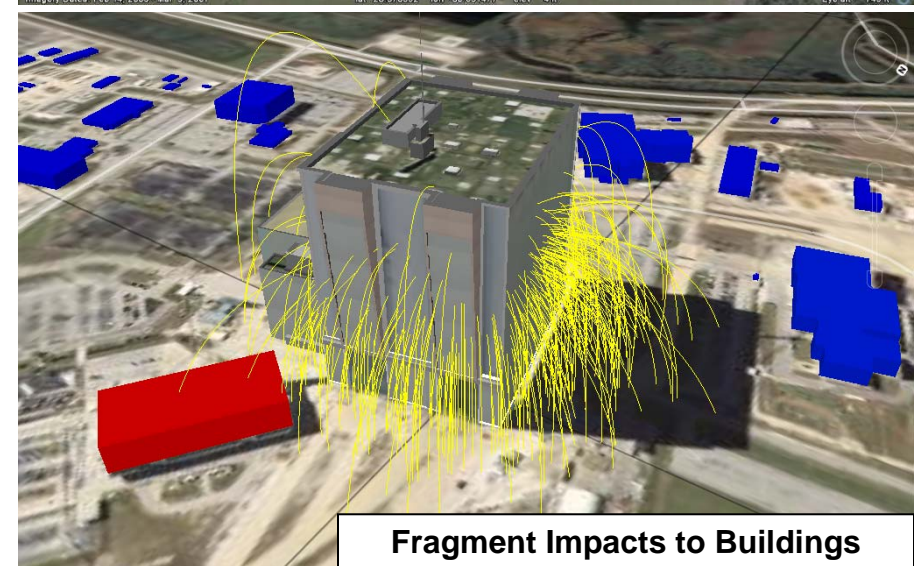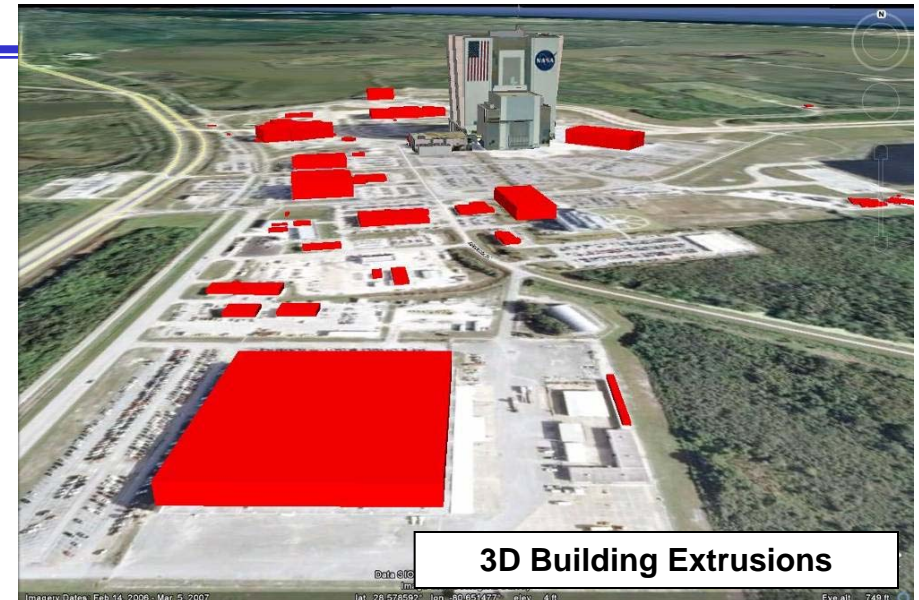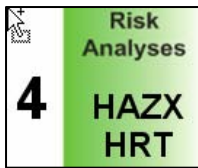

- **Window breakage could cause injuries but unlikely to cause fatalities**

Fragment Consequence Analysis
(given explosion occurs)

- **Occupied buildings adjacent to VAB were extruded to their respective heights**

- **Fragment penetration energies were assigned to walls and roofs based on building construction**

- **Fragment trajectories were tracked (including bounce) and impacts/penetrations recorded for thousands of random simulations**

- **Analysis showed that several buildings inside IBD could penetrated and potentially hazard occupants**

3D Building Extrusions

Fragment Impacts to Buildings

10

Risk Analyses

4 Risk Analyses HAZX HRT

(note: NASA does not currently accept risk analyses for ground safety)

- **Simplified quantitative risk analyses were performed to complete the DDESB explosion assessment process**

- **The probability of a SC processing accident was based on historical accident data for vehicle launches from the VAFB, CCAFS and KSC**

- **Two acceptable risk criteria were evaluated:**

  - *DDESB conventional weapons criteria based on fatalities*
    - Annual maximum individual and group risk

  - *Range Safety Guidelines (RCC 327-01) based on casualties (serious injury or greater) and fatalities*
    - Per mission maximum individual and group risk
    - Annual group risk

- **The risk is acceptable per DDESB's annual fatality risk criteria**

- **The risk is unacceptable per RCC 327-01's per mission casualty criteria**

REASON – glass breakage can cause injuries inside & outside IBD but highly unlikely to cause fatalities

Conclusions & Recommendations

- **Explosives siting analyses were performed following the four steps in the process recommended by the DDESB**
  - *The explosives standards Q-D distance was shown to be overly conservative based on an vehicle-specific equivalent protection analysis*
  - *Consequence analyses indicated that several buildings inside IBD could be hazarded by window breakage and fragment penetration given the accident occurs*
  - *Simplified risk analyses showed that acceptability was a function of the acceptable risk criteria*
    - **Injuries due to window breakage is an important consideration**
- **Performing all four steps of the explosion assessment process provides valuable insights to help a decision-maker understand all the hazards/risks and determine best mitigation strategy**